hacspec

a gateway to high-assurance cryptography

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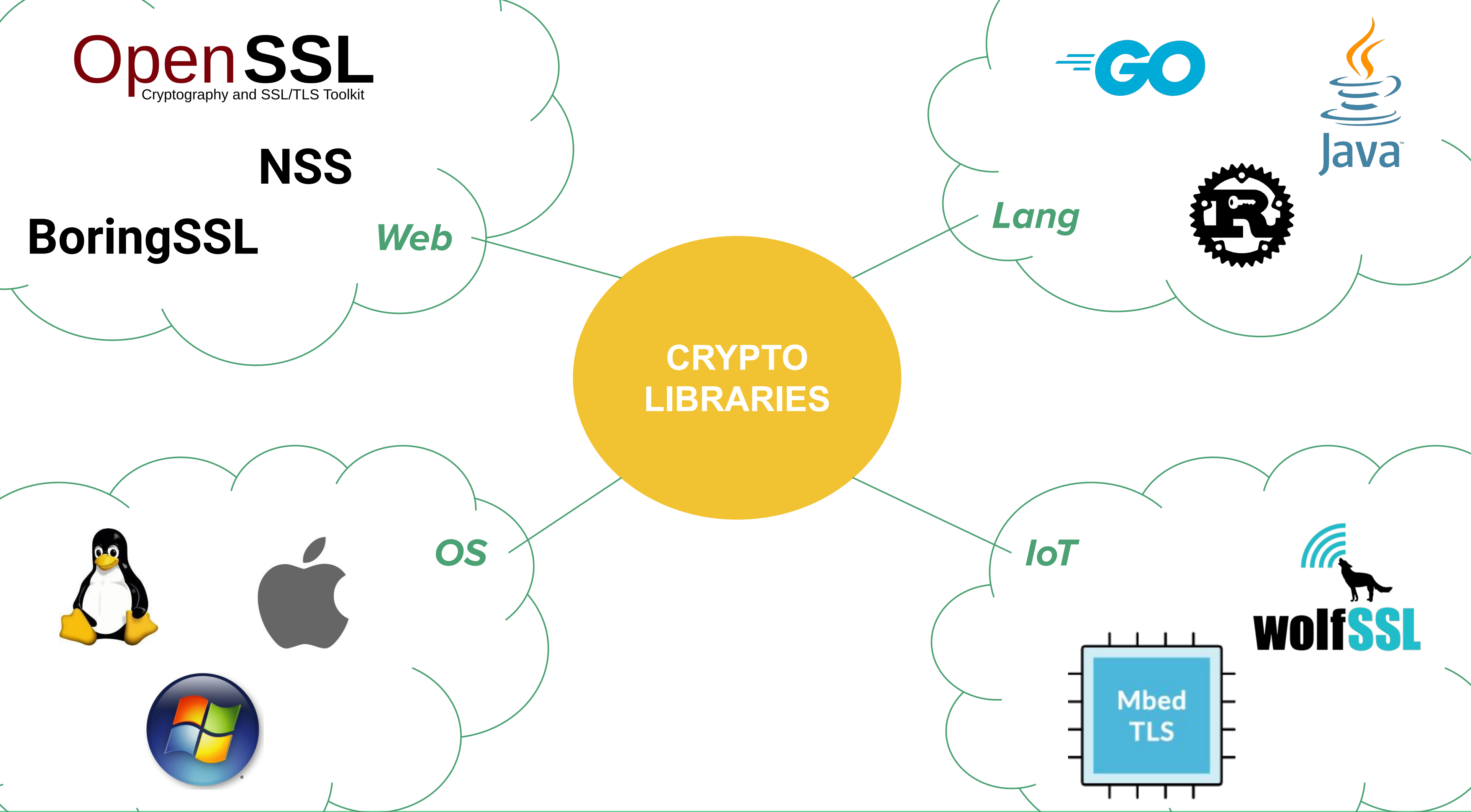
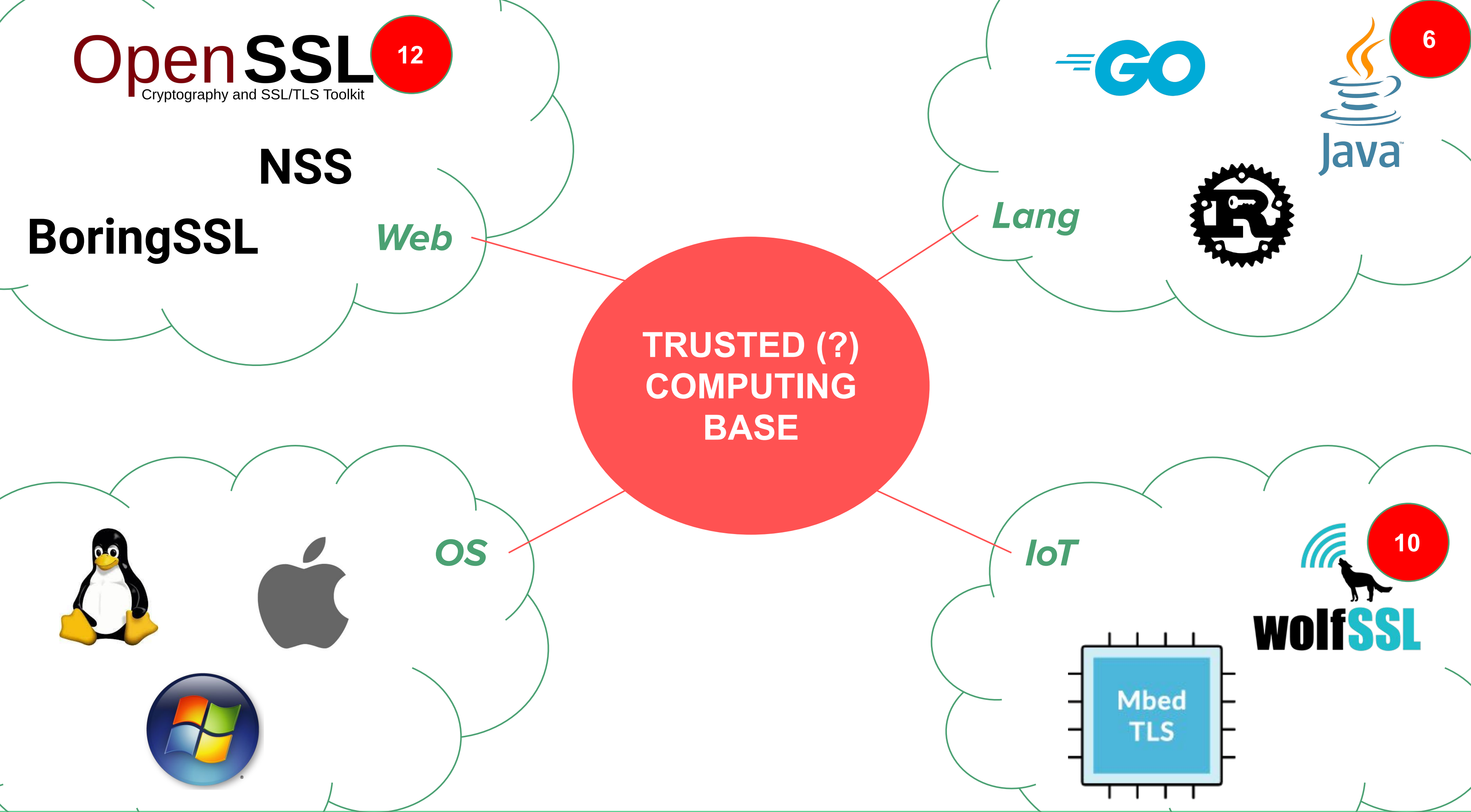

CRYPTO LIBRARIES
Web
OpenSSL
Cryptography and SSL/TLS Toolkit
NSS
BoringSSL
Lang
GO
Java
OS
IoT
wolfSSL
Mbed TLS


TRUSTED (?)
COMPUTING
BASE
Web
OpenSSL
Cryptography and SSL/TLS Toolkit
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NSS
BoringSSL
Lang
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IoT
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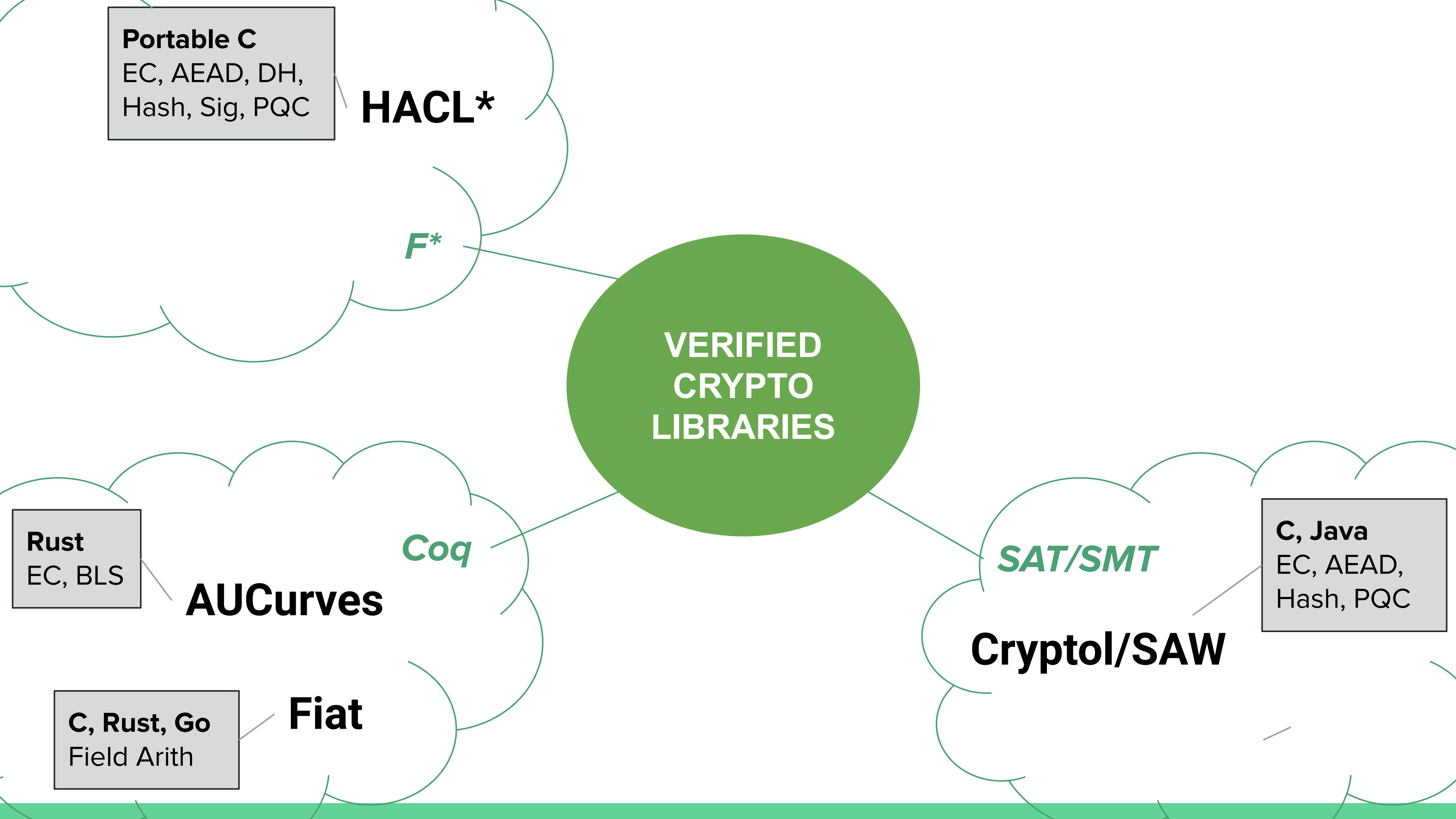
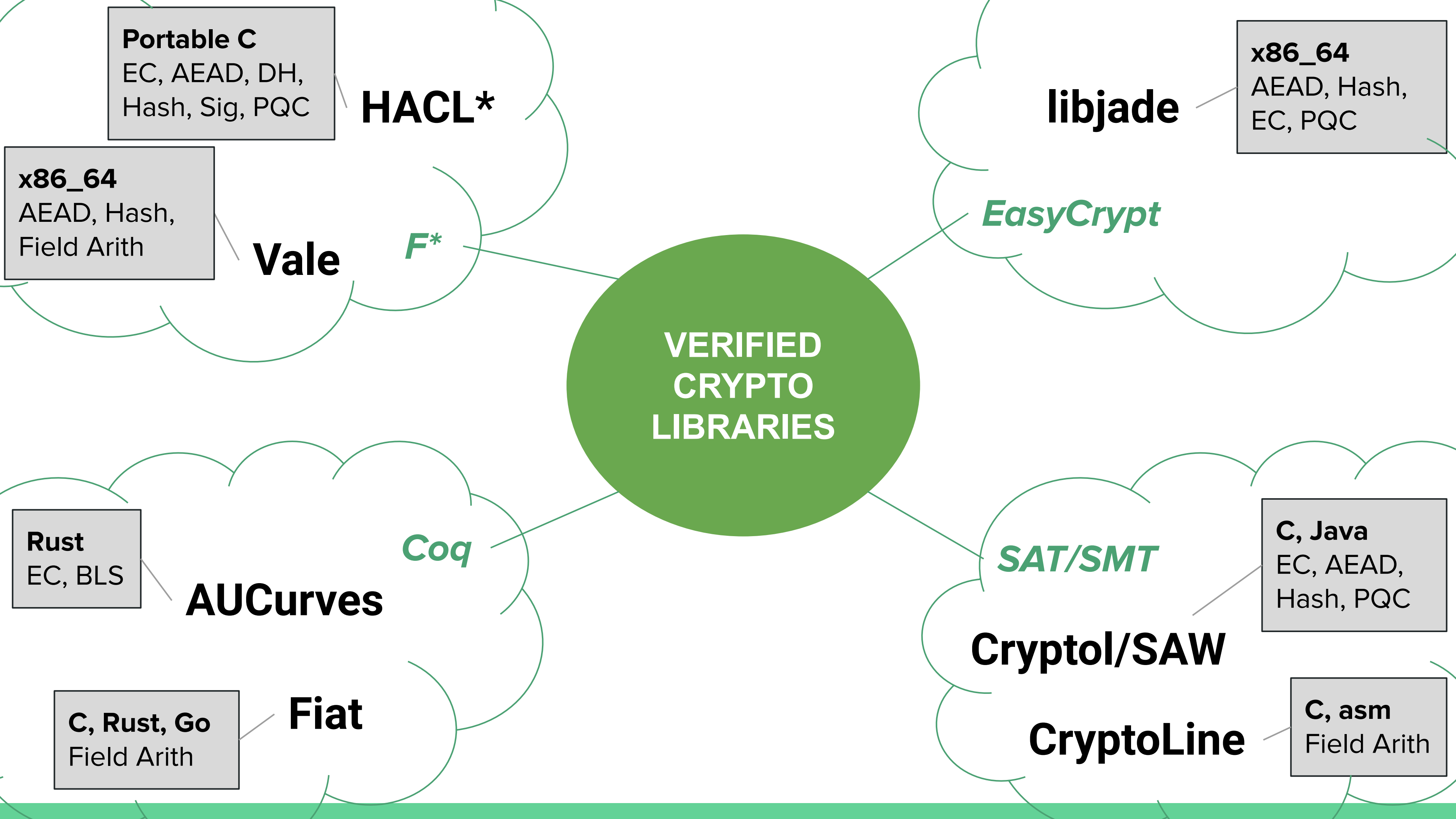

Portable C
EC, AEAD, DH, Hash, Sig, PQC
HACL*
F*
VERIFIED CRYPTO LIBRARIES
Rust
EC, BLS
AUCurves
Coq
C, Rust, Go
Field Arith
Fiat
SAT/SMT
C, Java
EC, AEAD, Hash, PQC
Cryptol/SAW


VERIFIED CRYPTO LIBRARIES
F*
HACL*
Portable C
EC, AEAD, DH, Hash, Sig, PQC
Vale
x86_64
AEAD, Hash, Field Arith
EasyCrypt
libjade
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C, Rust, Go
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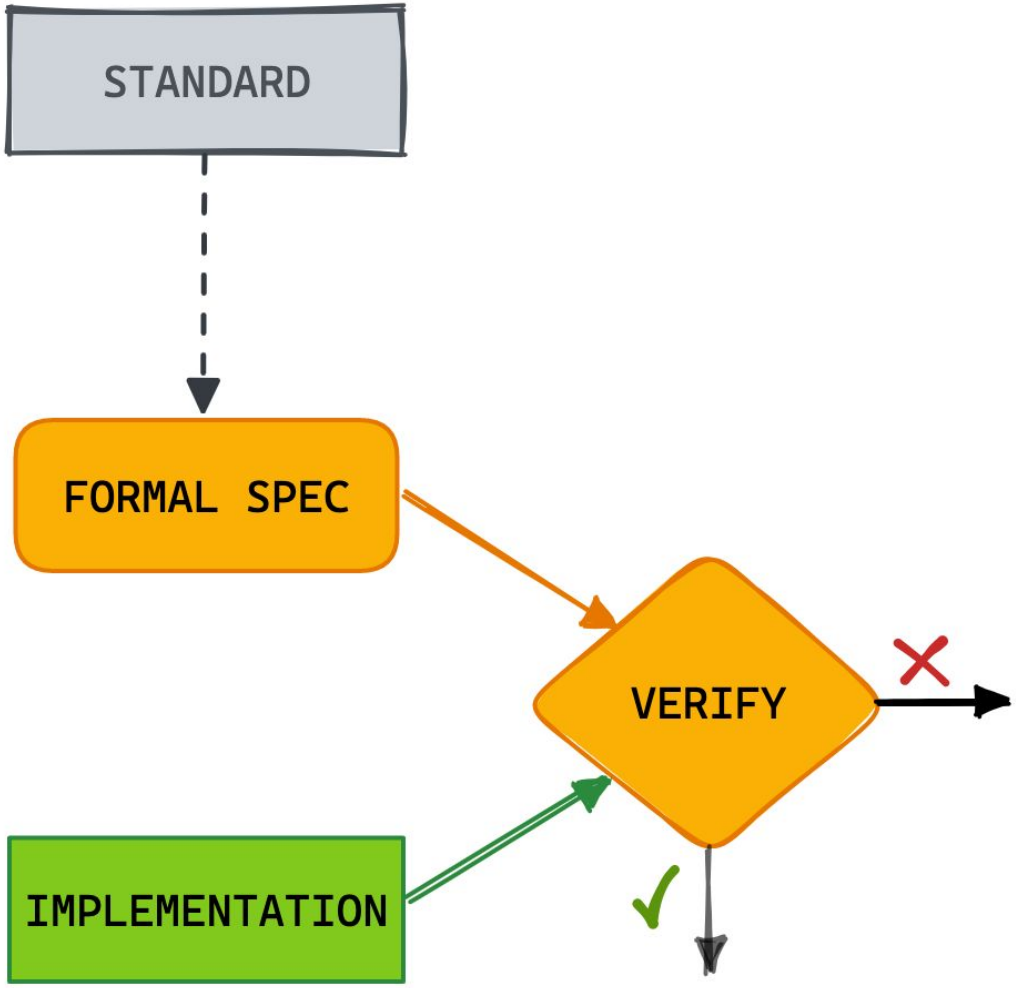
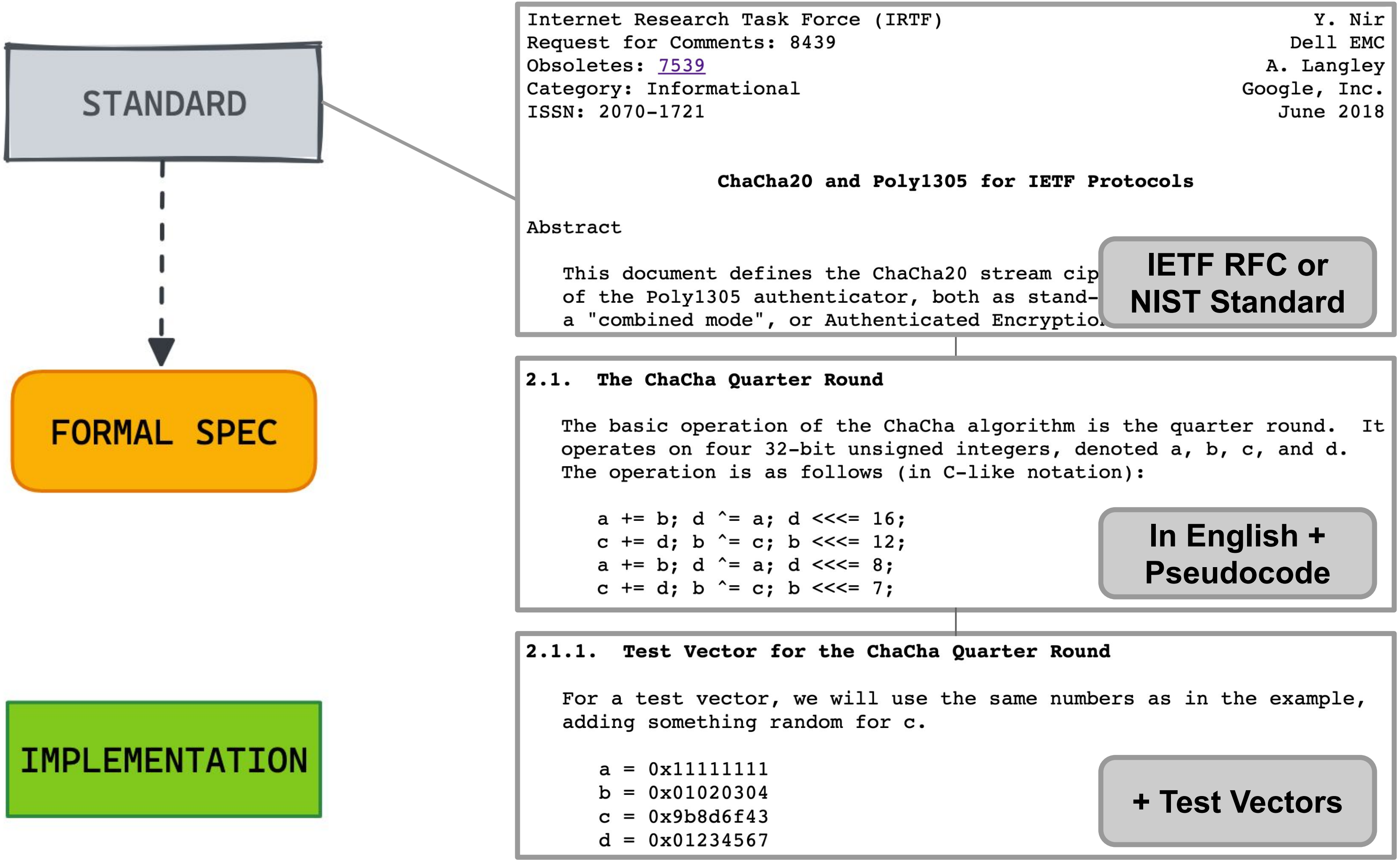
SAT/SMT
Cryptol/SAW
C, Java
EC, AEAD, Hash, PQC
CryptoLine
C, asm
Field Arith

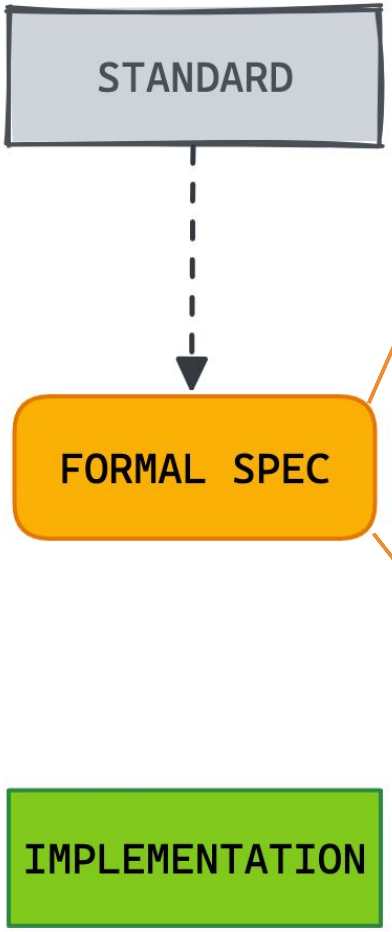
Good news: For any modern crypto algorithm, there is probably a verified implementation.

But... research code with low-level APIs, and specs written in unfamiliar formal languages.



Verified Cryptography Workflow


STANDARD
FORMAL SPEC
IMPLEMENTATION
Internet Research Task Force (IRTF)
Request for Comments: 8439
Obsoletes: 7539
Category: Informational
ISSN: 2070-1721
Y. Nir
Dell EMC
A. Langley
Google, Inc.
June 2018
ChaCha20 and Poly1305 for IETF Protocols
Abstract
This document defines the ChaCha20 stream cip
of the Poly1305 authenticator, both as stand-
a "combined mode", or Authenticated Encryptio
IETF RFC or NIST Standard
2.1. The ChaCha Quarter Round
The basic operation of the ChaCha algorithm is the quarter round. It operates on four 32-bit unsigned integers, denoted a, b, c, and d. The operation is as follows (in C-like notation):
a += b; d ^= a; d <<<= 16;
c += d; b ^= c; b <<<= 12;
a += b; d ^= a; d <<<= 8;
c += d; b ^= c; b <<<= 7;
In English + Pseudocode
2.1.1. Test Vector for the ChaCha Quarter Round
For a test vector, we will use the same numbers as in the example, adding something random for c.
a = 0x11111111
b = 0x01020304
c = 0x9b8d6f43
d = 0x01234567
+ Test Vectors

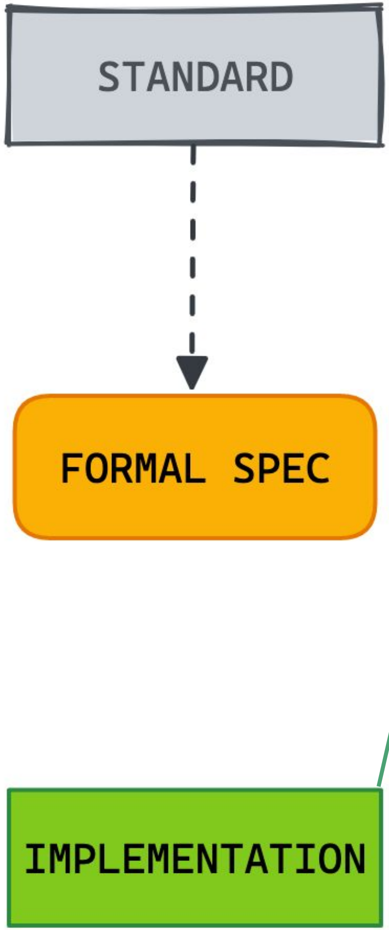



```
let line (a:idx) (b:idx) (d:idx) (s:rotval U32) (m:state) : Tot state =
  let m = m.[a] ← (m.[a] +. m.[b]) in
  let m = m.[d] ← ((m.[d] ^. m.[a]) <<<. s) in m

let quarter_round a b c d : Tot shuffle =
  line a b d (size 16) @
  line c d b (size 12) @
  line a b d (size 8)  @
  line c d b (size 7)
```

F* Spec
(HACL*)

```
proc chacha20_line(a : int, b : int, d : int, s : int, st : State) = {
  var state;
  state <- st;
  state.[a] <- ((state).[a]) + ((state).[b]);
  state.[d] <- ((state).[d]) `^` ((state).[a]);
  state.[d] <- rotate_left ((state).[d]) (s);
  return state;
}

proc chacha20_quarter_round(a : int, b : int, c : int, d : int, st : State) = {
  var state;
  state <@ chacha20_line (a, b, d, 16, st);
  state <@ chacha20_line (c, d, b, 12, state);
  state <@ chacha20_line (a, b, d, 8, state);
  state <@ chacha20_line (c, d, b, 7, state);
  return state;
}
```

EasyCrypt Spec
(libjade)



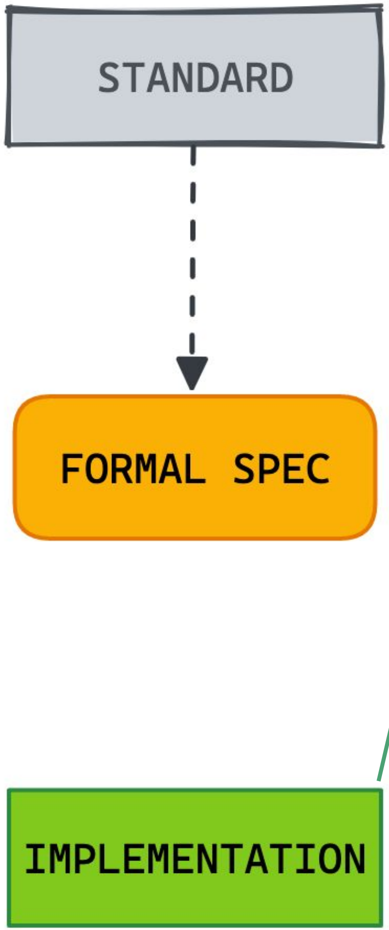
F* Implementation

```
let line st a b d r =
  let sta = st.(a) in
  let stb = st.(b) in
  let std = st.(d) in
  let sta = sta +. stb in
  let std = std ^. sta in
  let std = rotate_left std r in
  st.(a) ← sta;
  st.(d) ← std

let quarter_round st a b c d =
  line st a b d (size 16);
  line st c d b (size 12);
  line st a b d (size 8);
  line st c d b (size 7)
```

Translate

```
static inline void quarter_round(uint32_t *st, uint32_t a, uint32_t b, uint32_t c, uint32_t d)
{
  uint32_t sta = st[a];
  uint32_t stb0 = st[b];
  uint32_t std0 = st[d];
  uint32_t sta10 = sta + stb0;
  uint32_t std10 = std0 ^ sta10;
  uint32_t std2 = std10 << (uint32_t)16U | std10 >> (uint32_t)16U;
  st[a] = sta10;
  st[d] = std2;
  ...
```

Portable C Code



Jasmin Implementation

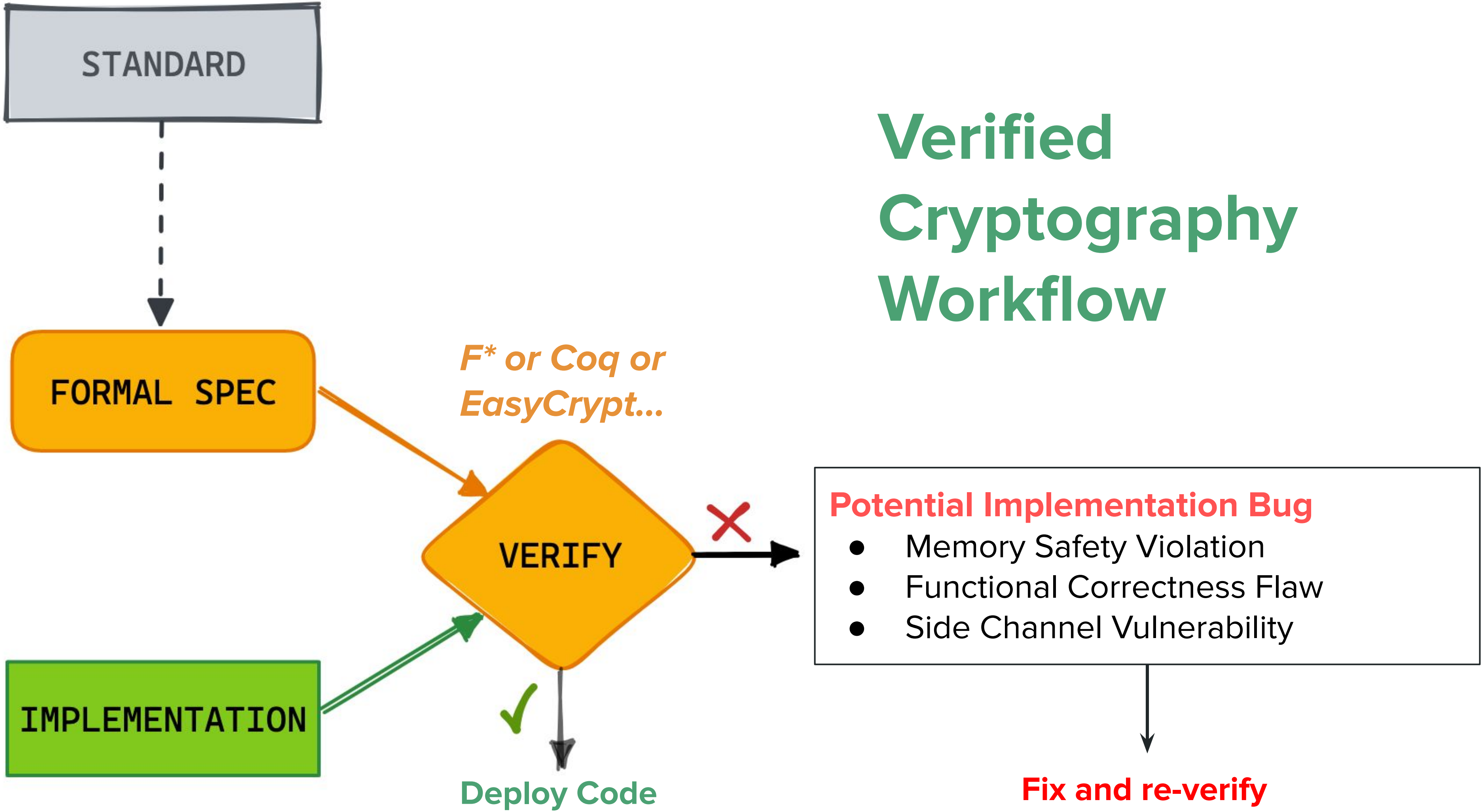
```
inline fn __line_ref(reg u32[16] k,
                     inline int a b c r)
                     -> reg u32[16]
{
  k[a] += k[b];
  k[c] ^= k[a];
  _, _, k[c] = #ROL_32(k[c], r);
  return k;
}

inline fn __quarter_round_ref(reg u32[16] k,
                              inline int a b c d)
                              -> reg u32[16]
{
  k = __line_ref(k, a, b, d, 16);
  k = __line_ref(k, c, d, b, 12);
  k = __line_ref(k, a, b, d, 8);
  k = __line_ref(k, c, d, b, 7);
  return k;
}
```

Translate

Intel AVX2 Assembly

```
vpaddd  %ymm4, %ymm0, %ymm0
vpxor   %ymm0, %ymm12, %ymm12
vpshufb (%rsp), %ymm12, %ymm12
vpaddd  %ymm12, %ymm8, %ymm8
vpaddd  %ymm6, %ymm2, %ymm2
vpxor   %ymm8, %ymm4, %ymm4
vpxor   %ymm2, %ymm14, %ymm14
vpslld  $12, %ymm4, %ymm15
vpsrld  $20, %ymm4, %ymm4
vpxor   %ymm15, %ymm4, %ymm4
vpshufb (%rsp), %ymm14, %ymm14
vpaddd  %ymm4, %ymm0, %ymm0
vpaddd  %ymm14, %ymm10, %ymm10
vpxor   %ymm0, %ymm12, %ymm12
vpxor   %ymm10, %ymm6, %ymm6
vpshufb 32(%rsp), %ymm12, %ymm12
vpslld  $12, %ymm6, %ymm15
vpsrld  $20, %ymm6, %ymm6
...
```

Verified Cryptography Workflow



Good news: For any modern crypto algorithm, there is probably a verified implementation

- You don’t have to sacrifice performance
- Mechanized proofs that you can run and re-run yourself
- You (mostly) don’t have to read or understand the proofs

But… not always easy to use, extend, or combine code from different libraries

- You do need to carefully audit the formal specs, written in tool-specific spec languages like F*, Coq, EasyCrypt
- You do need to safely use their low-level APIs, which often embed subtle pre-conditions

hacspec: a tool-independent spec language

Design Goals

- **Easy to use** for crypto developers
- **Familiar** language and tools
- **Succinct** specs, like pseudocode
- **Strongly typed** to avoid spec errors
- **Executable** for spec debugging
- **Testable** against RFC test vectors
- **Translations** to formal languages like

  F*, Coq, EasyCrypt, ...

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A purely functional subset of Rust

- Safe Rust without external side-effects
- No mutable borrows
- All values are copyable
- Rust tools & development environment
- A library of common abstractions
  - Arbitrary-precision Integers
  - Secret-independent Machine Ints
  - Vectors, Matrices, Polynomials,...

Language and Toolchain Details: hacspec.org

hacspec: purely functional crypto code in Rust

```
inner_block (state):
   Qround(state, 0, 4, 8, 12)
   Qround(state, 1, 5, 9, 13)
   Qround(state, 2, 6, 10, 14)
   Qround(state, 3, 7, 11, 15)
   Qround(state, 0, 5, 10, 15)
   Qround(state, 1, 6, 11, 12)
   Qround(state, 2, 7, 8, 13)
   Qround(state, 3, 4, 9, 14)
   end
```

ChaCha20 RFC

Call-by-value

```
fn inner_block(st: State) -> State {
   let mut state = st;
   state = chacha20_quarter_round(0, 4, 8, 12, state);
   state = chacha20_quarter_round(1, 5, 9, 13, state);
   state = chacha20_quarter_round(2, 6, 10, 14, state);
   state = chacha20_quarter_round(3, 7, 11, 15, state);
   state = chacha20_quarter_round(0, 5, 10, 15, state);
   state = chacha20_quarter_round(1, 6, 11, 12, state);
   state = chacha20_quarter_round(2, 7, 8, 13, state);
   chacha20_quarter_round(3, 4, 9, 14, state)
}
```

State-passing style

ChaCha20 in hacspec

hacspec: abstract integers for field arithmetic

```
n = le_bytes_to_num(msg[((i-1)*16)..(i*16)] | [0x01])
a += n
a = (r * a) % p
```

Poly1305 RFC (update_block)

Modular 130-bit Prime Field Arithmetic

```
pub fn poly1305_encode_block(b: &PolyBlock) -> FieldElement {
    let n = U128_from_le_bytes(U128Word::from_seq(b));
    let f = FieldElement::from_secret_literal(n);
    f + FieldElement::pow2(128)
}

pub fn poly1305_update_block(b: &PolyBlock, (acc,r,s): PolyState) -> PolyState {
    ((poly1305_encode_block(b) + acc) * r, r, s)
}
```

Poly1305 in hacspec

Modular Arithmetic over User-Defined Field

hacspec: secret integers for “constant-time” code

Separate Secret and Public Values

- New types: U8, U32, U64, U128
- Can do arithmetic: +, *, -
- Can do bitwise ops: ^, |, &
- Cannot do division: /, %
- Cannot do comparison: ==, !=, <, ...
- Cannot use as array indexes: x[u]

Enforces secret independence

- A “constant-time” discipline
- Important for some crypto specs

```
fn chacha20_line(a: StateIdx, b: StateIdx, d: StateIdx,
                 s: usize, mut state: State) -> State {
    state[a] = state[a] + state[b];
    state[d] = state[d] ^ state[a];
    state[d] = state[d].rotate_left(s);
    state
}
```

ChaCha20 in hacspec

```
fn sub_bytes(state: Block) -> Block {
    let mut st = state;
    for i in 0..BLOCKSIZE {
        st[i] = SBOX[U8::declassify(state[i])];
    }
    st
}
```

AES in hacspec

hacspec: translation to formal languages

```
pub fn chacha20_quarter_round(
    a: StateIdx,
    b: StateIdx,
    c: StateIdx,
    d: StateIdx,
    mut state: State,
) -> State {
    state = chacha20_line(a, b, d, 16, state);
    state = chacha20_line(c, d, b, 12, state);
    state = chacha20_line(a, b, d, 8, state);
    chacha20_line(c, d, b, 7, state)
}
```

ChaCha20 in hacspec

```
let chacha20_quarter_round (a b c d: state_idx_t) (state: state_t) : state_t =
  let state:state_t = chacha20_line a b d 16 state in
  let state:state_t = chacha20_line c d b 12 state in
  let state:state_t = chacha20_line a b d 8 state in
  chacha20_line c d b 7 state
```

F* Spec

```
Definition chacha20_quarter_round (a : int32) (b : int32) (c : int32)
                                  (d : int32) (state : State) : State :=
  let state := chacha20_line a b d 16 state : State in
  let state := chacha20_line c d b 12 state : State in
  let state := chacha20_line a b d 8 state : State in
  chacha20_line c d b 7 state.
```

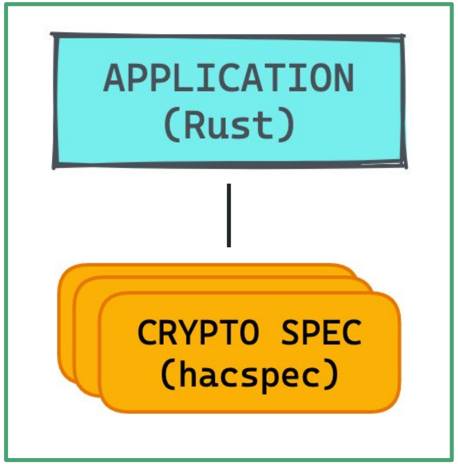
Coq Spec

```
proc chacha20_quarter_round(a : int, b : int, c : int, d : int,
                            state : State) = {
  var _res;
  state <@ chacha20_line (a, b, d, 16, state);
  state <@ chacha20_line (c, d, b, 12, state);
  state <@ chacha20_line (a, b, d, 8, state);
  _res <@ chacha20_line (c, d, b, 7, state);
  return _res;
}
```

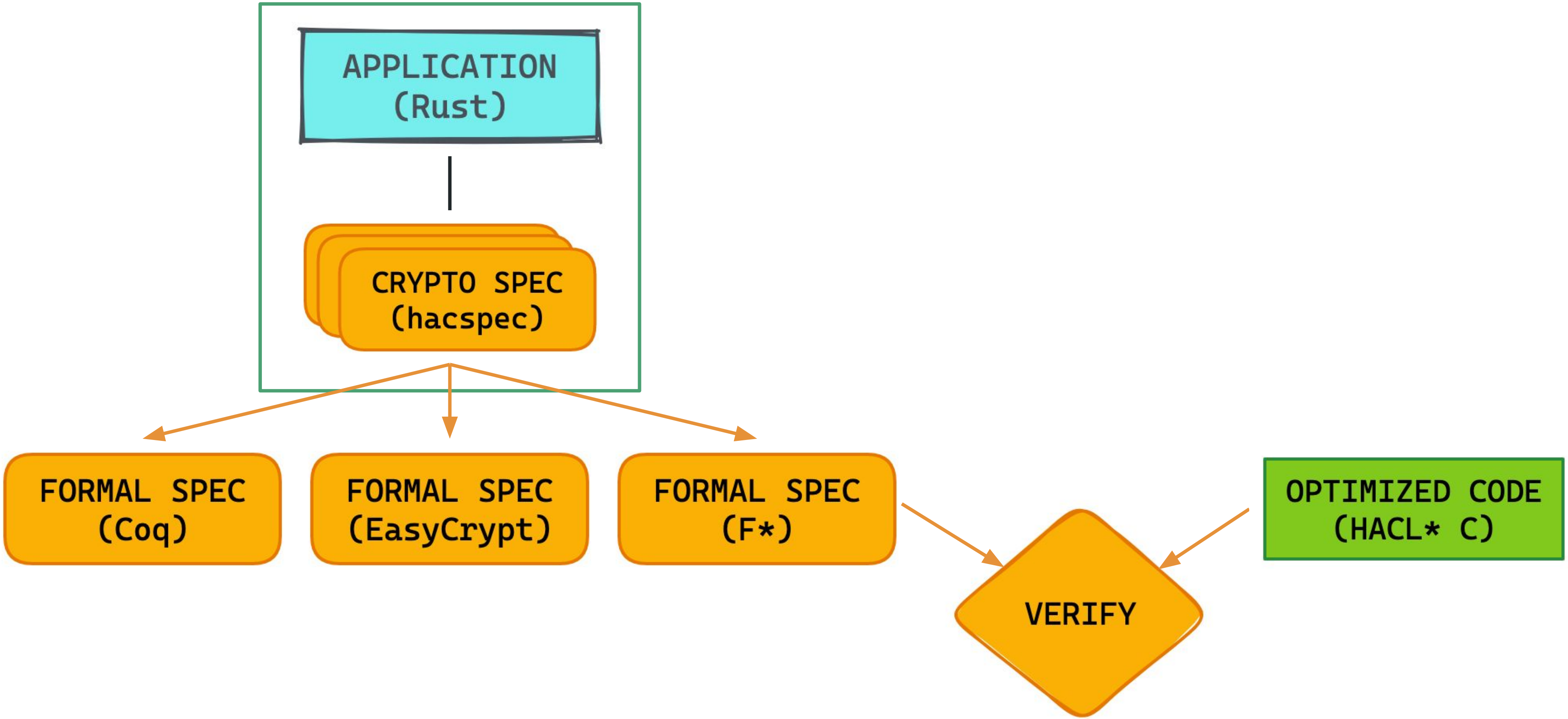
EasyCrypt Spec

Active development: github.com/hacspec

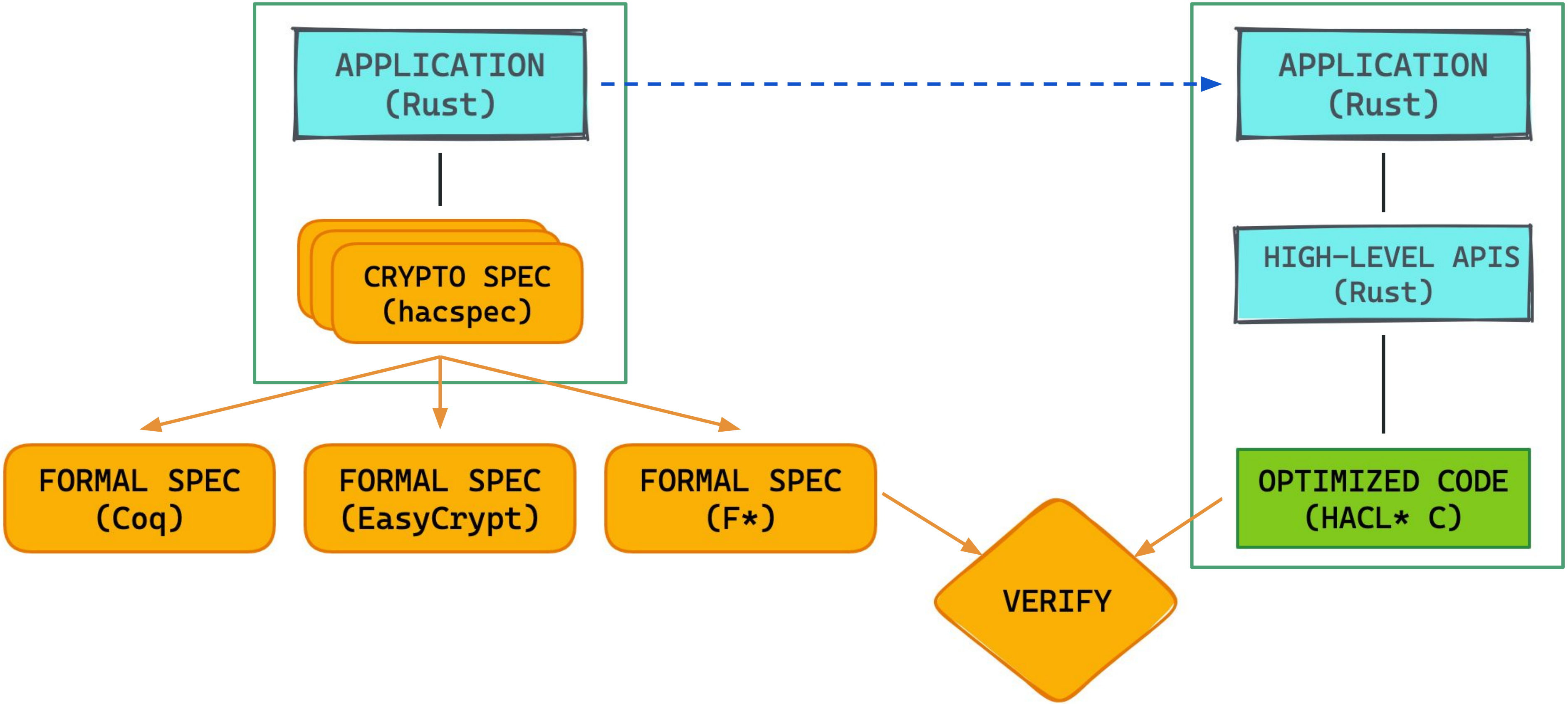
hacspec: towards high-assurance crypto software



hacspec: towards high-assurance crypto software

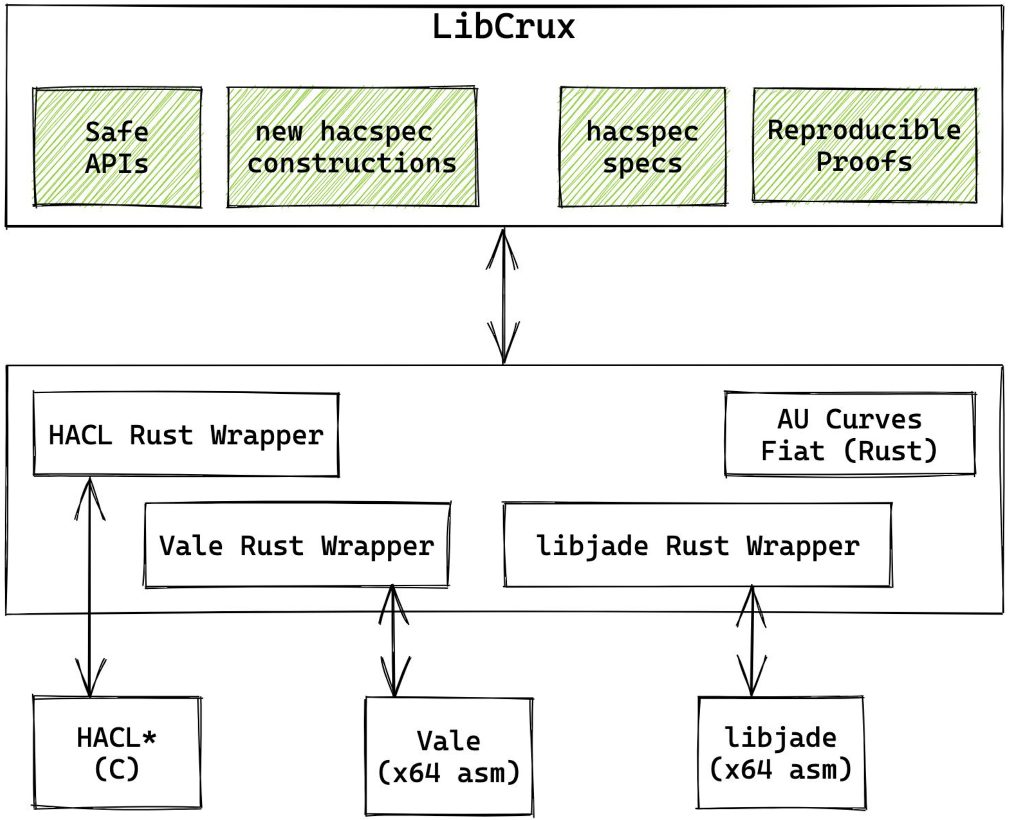


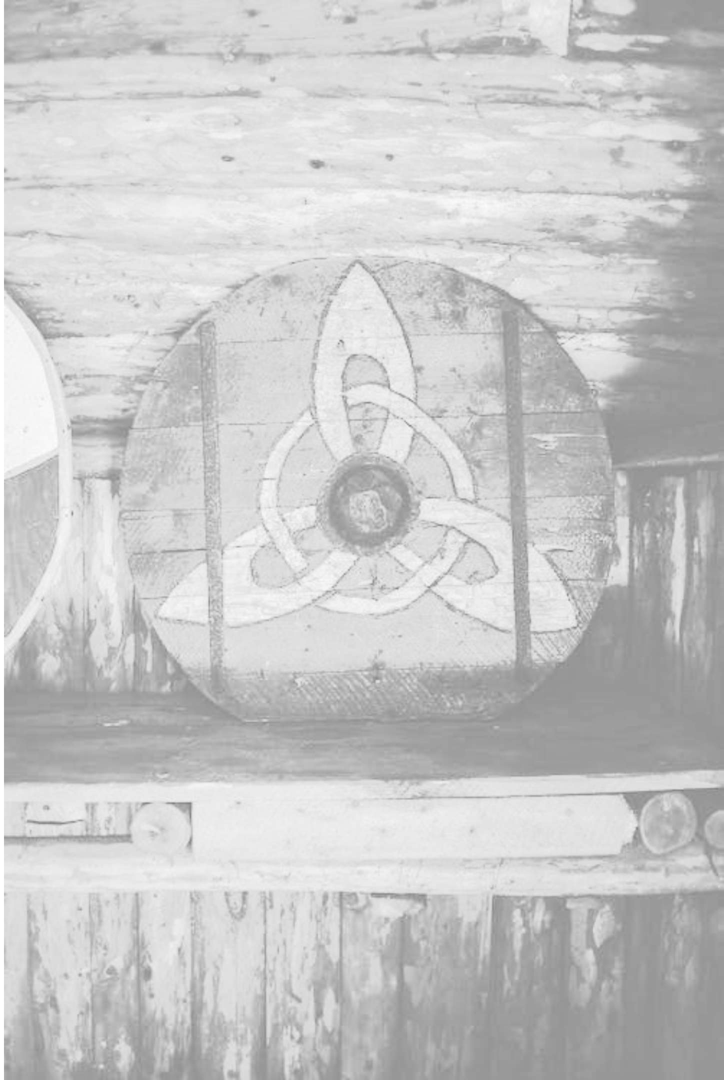
hacspec: towards high-assurance crypto software



libcrux: a library of verified cryptography

libcrux: architecture





Unsafe APIs: Array Constraints

```
void
Hacl_Chacha20Poly1305_32_aead_encrypt(
  uint8_t *k,
  uint8_t *n,
  uint32_t aadlen,
  uint8_t *aad,
  uint32_t mlen,
  uint8_t *m,
  uint8_t *cipher,
  uint8_t *mac
);
```

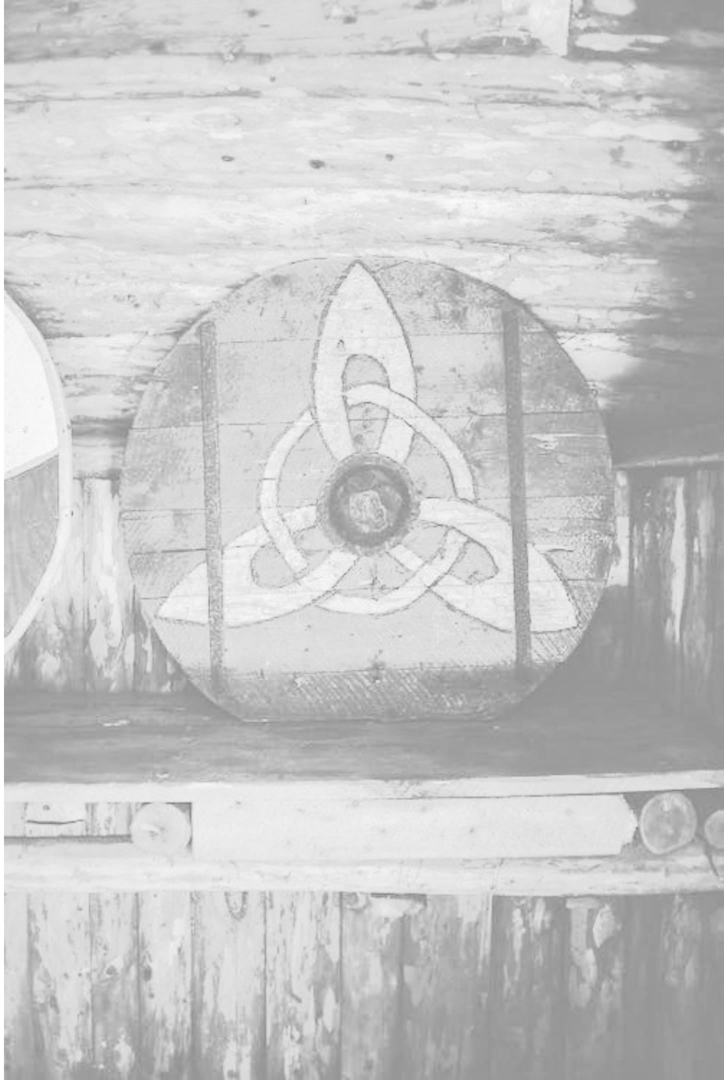
Fixed Length (k, n)

Disjoint (cipher, mac)

Verified F* API: Preconditions

```
let aead_encrypt_st (w:field_spec) =
    key:lbuffer uint8 32ul
  -> nonce:lbuffer uint8 12ul
  -> alen:size_t
  -> aad:lbuffer uint8 alen
  -> len:size_t
  -> input:lbuffer uint8 len
  -> output:lbuffer uint8 len
  -> tag:lbuffer uint8 16ul ->
  Stack unit
  (requires fun h ->
    live h key /\ live h nonce /\ live h aad /\
    live h input /\ live h output /\ live h tag /\
    disjoint key output /\ disjoint nonce output /\
    disjoint key tag /\ disjoint nonce tag /\
    disjoint output tag /\ eq_or_disjoint input output /\
    disjoint aad output)
```

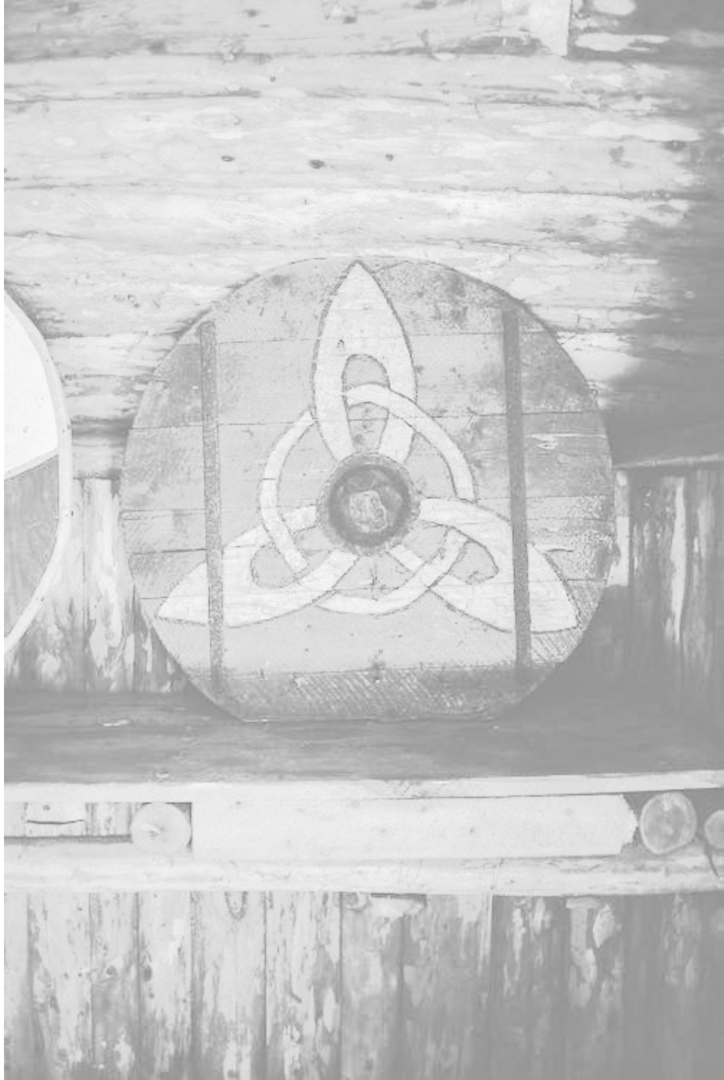
Length Constraints



Verified F* API: Preconditions

```
let aead_encrypt_st (w:field_spec) =
    key:lbuffer uint8 32ul
  -> nonce:lbuffer uint8 12ul
  -> alen:size_t
  -> aad:lbuffer uint8 alen
  -> len:size_t
  -> input:lbuffer uint8 len
  -> output:lbuffer uint8 len
  -> tag:lbuffer uint8 16ul ->
  Stack unit
  (requires fun h ->
    live h key /\ live h nonce /\ live h aad /\
    live h input /\ live h output /\ live h tag /\
    disjoint key output /\ disjoint nonce output /\
    disjoint key tag /\ disjoint nonce tag /\
    disjoint output tag /\ eq_or_disjoint input output /\
    disjoint aad output)
```

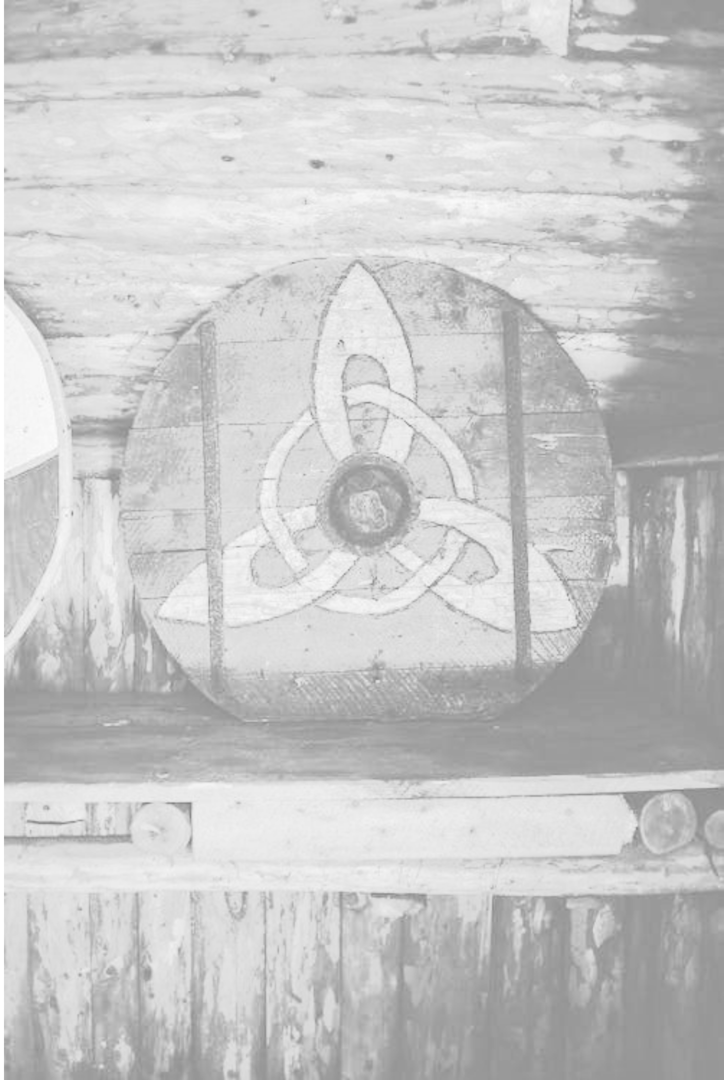
Disjointness Constraints



libcrux: Typed Rust APIs

```rust
type Chacha20Key = [u8; 32];
type Nonce = [u8; 12];
type Tag = [u8; 16];

fn encrypt(
    key: &Chacha20Key,
    msg_ctxt: &mut [u8],
    nonce: Nonce,
    aad: &[u8]
) -> Tag
```



libcrux: supported algorithms & perf

Crypto Standard	Platforms	Specs	Implementations
ECDH • x25519 • P256	 Portable + Intel ADX Portable	 hacspec, F* hacspec, F*	 HACL*, Vale HACL*
AEAD • Chacha20Poly1305 • AES-GCM	 Portable + Intel/ARM SIMD Intel AES-NI	 hacspec, F*, EasyCrypt hacspec, F*	 HACL*, libjade Vale
Signature • Ed25519 • ECDSA P256 • BLS12-381	 Portable Portable Portable	 hacspec, F* hacspec, F* hacspec, Coq	 HACL* HACL* AUCurves
Hash • Blake2 • SHA2 • SHA3	 Portable + Intel/ARM SIMD Portable Portable + Intel SIMD	 hacspec, F* hacspec, F* hacspec, F*, EasyCrypt	 HACL* HACL* HACL*, libjade
HKDF, HMAC	Portable	hacspec, F*	HACL*
HPKE	Portable	hacspec	hacspec

libcrux: performance

	libcrux	Rust Crypto	Ring	OpenSSL
Sha3 256	574.39 MiB/s	573.89 MiB/s	unsupported	625.37 MiB/s
x25519	30.320 µs	35.465 µs	30.363 µs	32.272 µs

libjade

HACL* + Vale

Intel Kaby Lake (ADX, AVX2)

	libcrux	Rust Crypto	Ring	OpenSSL
Sha3 256	337.67 MiB/s	275.05 MiB/s	unsupported	322.21 MiB/s
x25519	37.640 µs	67.660 µs	71.236 µs	48.620 µs

HACL*

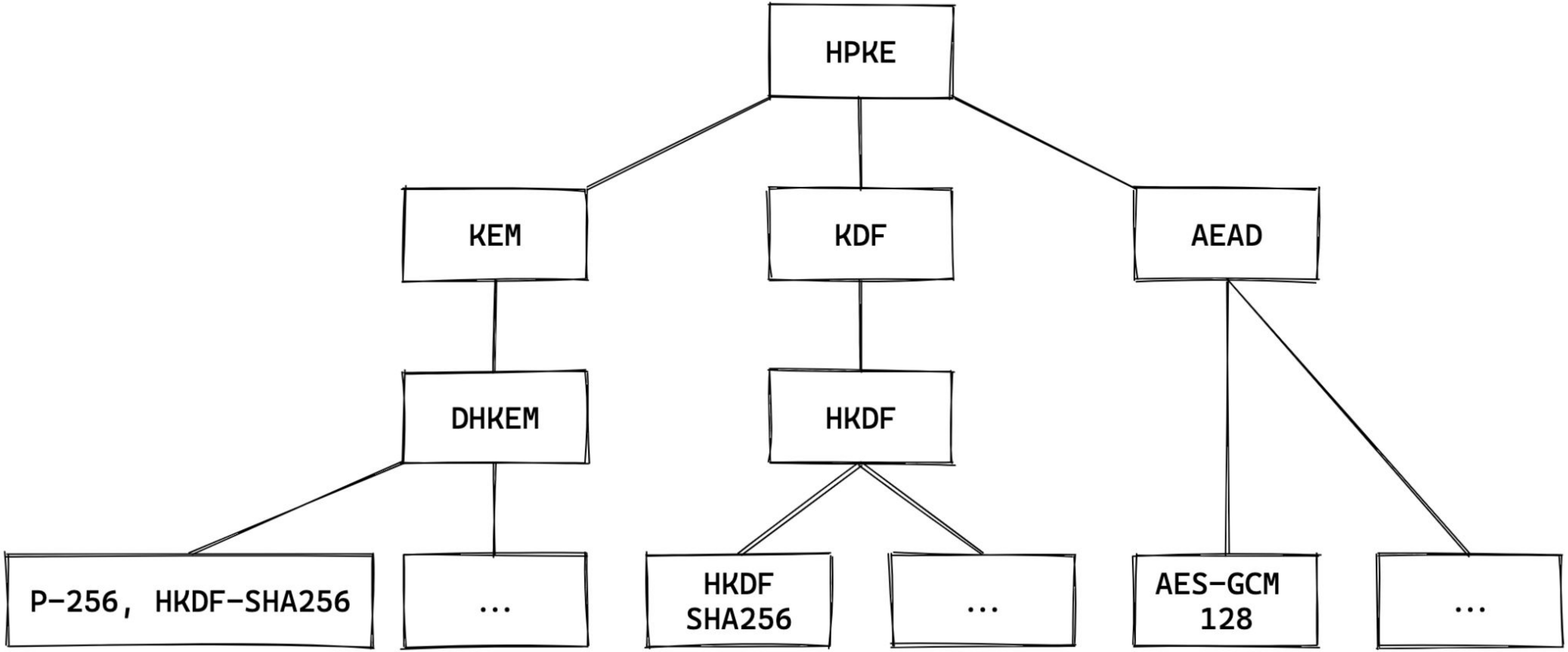
Apple Arm M1 Pro (Neon)

Stream:	Internet Research Task Force (IRTF)			
RFC:	9180			
Category:	Informational			
Published:	February 2022			
ISSN:	2070-1721			
Authors:	R. Barnes	K. Bhargavan	B. Lipp	C. Wood
	Cisco	*Inria*	*Inria*	*Cloudflare*

RFC 9180
Hybrid Public Key Encryption

https://tech.cryspen.com/hpke-spec/hpke/index.html

HPKE: Construction



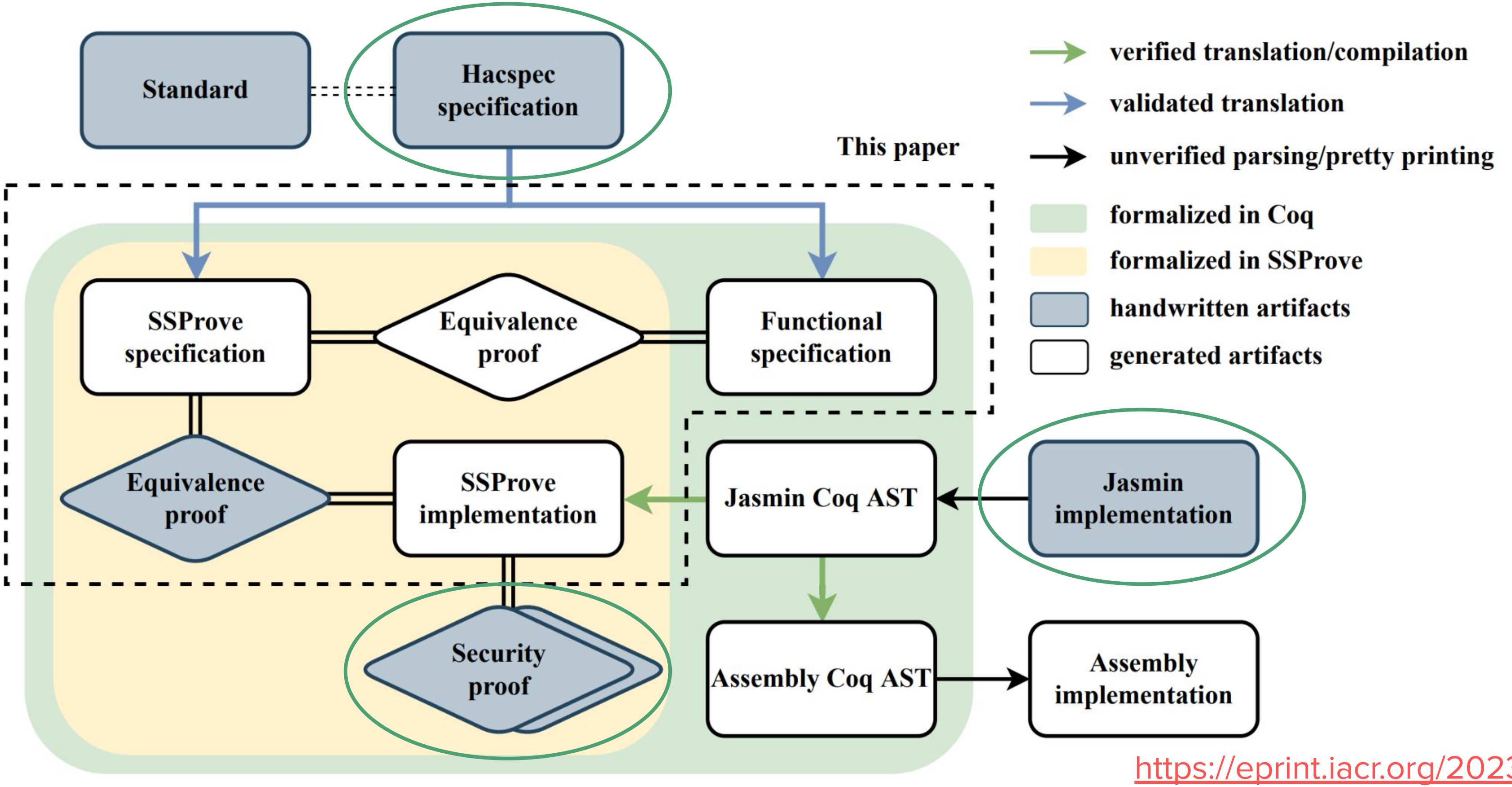
HPKE code performance: hacspec vs. stateful Rust

	hacspec HPKE	Rust HPKE
Setup Sender	79.9 µs	68 µs
Setup Receiver	76 µs	54.4 µs

	libcrux	RustCrypto
Sha2 256	311.76 MiB/s	319.10 MiB/s
x25519	30.320 µs	35.465 µs
x25519 base	30.218 µs	11.812 µs
ChaCha20Poly1305	758.89 MiB/s	249.33 MiB/s

Ongoing and Future Work

The Last Yard: linking hacspec to security proofs



https://eprint.iacr.org/2023/185

Verification Tools: more proof backends for hacspec

Security Analysis Tools

- SSProve: modular crypto proofs
- EasyCrypt: verified constructions

- ProVerif: symbolic protocol proofs
- CryptoVerif: verified protocols
- Squirrel: protocol verifier

Program Verification Tools

- QuickCheck: logical spec testing
- Creusot: verifying spec contracts
- Aeneas: verifying Rust code

- LEAN: verification framework
- <Your favourite prover here>

Conclusions

- **Fast verified code** is available today for most modern crypto algorithms
  - + some post-quantum crypto; Future: verified code for ZKP, FHE, MPC, …
  - Most code in C or Intel assembly; Ongoing: Rust, ARM assembly, …
- **hacspec** can be used as a common spec language for multiple tools/libraries
  - Ongoing: adding new Rust features, new proof backends, linking with Rust verifiers, …
  - **Try it yourself:** hacspec.org
- **libcrux** provides safe Rust APIs to multiple verified crypto libraries
  - Ongoing: recipes for integrating new verified crypto from various research projects
  - **Try it yourself:** libcrux.org

Thanks!

- HACL*: https://github.com/hacl-star/hacl-star
- Vale: https://github.com/ValeLang/Vale
- libjade: https://github.com/formosa-crypto/libjade
- AUCurves: https://github.com/AU-COBRA/AUCurves

- hacspec: https://github.com/hacspec/hacspec
- libcrux: https://github.com/cryspen/libcrux